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<p>We have introduced and studied new promising systems, which could lead to experimental verification and device applications of current driven plasma instabilities in lower dimensional solid state systems. These are: periodically modulated systems, quasi-1D bounded systems, and bounded systems with slab geometry. An interactive program for experimental verification of our results has been set-up with the Technical University, Vienna, Austria. The periodically modulated systems require significantly lower drift velocities compared to uniform systems to produce the plasma instabilities, bringing them within reach of experimental verification. In the bounded systems, with proper injection and extraction of carriers to maintain the desired non-equilibrium distribution, we obtain strong plasma instabilities, with a good chance for experimental observation. Possibility of population inversion in these latter structures is inferred by comparing our calculated I-V curves with the experimental curves. A decisive test for plasma instability in these structures is to look for radiation in the predicted frequency range. Such experiments, using bow-tie antennas, are planned for the near future. New formalisms were developed for the calculation of plasma instabilities in bounded systems (Energy Level Pairs Formalism), interlevel transport (self energy in random phase approximation), and extraction rates (transfer matrix poles).</p>			
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**Generation and Amplification of Radiation in Millimeter/  
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in Modulated Lower Dimensional Solid State Systems**

**Final Progress Report**

P. Bakshi and K. Kempa

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## I. Introduction

In this program we have introduced and studied new promising systems, which could lead to experimental verification and device applications of current driven plasma instabilities (CDPI) in lower dimensional solid state systems. These are: a) periodically modulated systems, b) quasi-1D bounded systems, c) bounded systems with slab geometry.

We have also set-up an interactive program for experimental verification of our results, with the Institut for Solid State Electronics at the Technical University of Vienna, Austria.

Several papers have been published, or submitted for publication, on the basis of work on this program. Several other presentations (e.g. APS March Meetings, and other Conferences) were also made, on the basis of this work.

The theoretical developments during this project, and the experimental results to date which broadly confirm some of our results, indicate that the main goal of this program, viz. the generation of (a) plasma instabilities, and (b) the ensuing electromagnetic radiation, in the terahertz (THz) range may be realized in the near future.

Section II provides a statement of the problems studied, section III summarizes the most important results and the last section lists the publications, and the participating scientific personnel.

## II. Statement of the Problem

The basic problem investigated (theoretically) in this program was the study of CDPI in various lower dimensional (non-uniform) solid state systems with the goal of developing a novel approach for the generation or amplification of electromagnetic radiation in the millimeter and submillimeter ranges, with potential applications to a new class of THz devices.

The basic principle is to utilize the energy of a dc current passing through a plasma, which leads to a plasma-instability. The instability mechanism transfers the energy from the current to characteristic plasma waves which grow in amplitude. These waves, in turn, can radiatively decay by interaction with a grating, by dipole charge oscillations or via a specially shaped antenna, emitting electromagnetic radiation in a predictable frequency range.

In an earlier program we had studied high mobility, lower dimensional, *uniform* systems. The required drift velocities, however, had to be of the order of or greater than

the Fermi velocities. In the present program we have examined the possibilities of *periodically modulated* systems, and also developed another new approach, based on *bounded* systems in quasi-1D, as well as, slab geometries. We find that the periodically modulated systems require significantly lower drift velocities to produce the plasma instabilities, bringing them within reach of experimental verification. In the bounded systems, with proper injection and extraction of carriers to maintain the desired non-equilibrium distribution, we obtain strong plasma instabilities, with a good chance for experimental observation.

An interactive collaborative program has been set-up with the Vienna group to work towards experimental verification of these ideas. Several joint Workshops, and mutual visits took place during this program, resulting in various joint publications.

### III. Main Results

There were five major areas covered in this program. We summarize below the main results:

#### 1. Periodic 1D systems, and lateral surface superlattices (LSSL)

We extended our earlier work on current driven plasma instabilities (CDPI) in modulated 1DEG to include multi-miniband structure and arbitrary drifts. We also set-up the formalism for non-sinusoidal, arbitrary periodic potentials. This was necessary for a self-consistent mean-field calculation which included the Hartree potential. We showed the feasibility of current driven plasma instabilities in lateral surface superlattices (2DEG with modulation in both directions). The dependence on the two periods, grid gate potential and the density of the electron gas was investigated.

We now have a complete self-consistent formalism for the calculation of the ground state and the RPA response for any given periodic external potential (of arbitrary shape and amplitude). We have also obtained an analytical formula for the potential generated by a grid of strip-electrodes situated at a height  $h$  above the wires. This can be generalized to obtain the potential generated for a 2DEG by a 2D grid gate, resulting in an LSSL. Using this formalism we have shown the feasibility of CDPI in 1D systems (modulated quantum wires) and in LSSL. These results have been presented at APS Meetings, and also form a part of the PhD thesis of H. Xie, (Ref. 1). Part of this work, along with a review of earlier work in uniform systems, has been published in Ref. 2.

We have also studied the plasma modes of modulated systems without currents, and are in the process of writing a comprehensive paper on the normal modes of quasi-1D periodically modulated plasmas, including their damping due to the periodicity induced single particle excitations. This latter aspect has not been discussed in the literature. We also obtain the zone boundary plasmons of this system, similar to those obtained for higher dimensional systems with periodic modulation. A paper describing these results (Ref. 3) will soon be submitted to Phys. Rev. B. A later paper will describe the instabilities in quasi-1D periodically modulated systems, and in lateral surface superlattices (LSSL).

## 2. Current driven plasma instabilities in quasi-1D bounded systems

Bounded systems (Ref. 2) offer significant advantages: 1) A bounded plasma has several eigenmodes, making it possible to pump the energy from the current to the plasma under a variety of conditions. A bounded system plays the role of a plasma mode resonator. 2) One can reduce the effects of collisions (impurity and phonon) by reducing the active size of the device below the corresponding mean free path, while the electron-electron interactions which sustain the collective modes are left intact. 3) Plasma oscillations of a bounded plasma couple directly to the electromagnetic radiation, through dipole charge oscillations, and no additional coupling mechanism is necessary to convert the plasma wave energy into electromagnetic radiation. 4) It may also be possible to achieve the anti-resonant conditions for acoustic phonons in a bounded plasma, achieving reduction of the phonon scattering.

In view of these possible advantages we began a systematic study of CDPI in the bounded plasmas. We showed theoretically (Ref. 4) the feasibility of strong plasma instability in quasi-1D bounded plasmas (quantum wires, few hundred nm long). Selective extraction and injection play an important role in achieving the population inversion necessary to generate the instability. Growth rates of about 1 meV were obtained both for superlattices and for simple quantum well geometries.

We have also showed that strong instabilities are obtained in slab geometry (unbounded in x and y directions, and of finite length in z direction). Again growth rates of 1-2 meV were obtained both for superlattices and for simple quantum well geometries.

## 3. Energy level pair formalism for plasma modes and instabilities

We have done all our previous calculations of instabilities within the random phase approximation (RPA), with a self-consistent ground state. While the full computer

programs give us the results for any specific scenario that we desire, the underlying simplicity (if any) does not necessarily come through in a computer calculation. In all our previous studies, including those on uniform, and periodically modulated (unbounded) systems, we had observed the importance of matching (single-particle) down transitions and up transitions in each case. The new *energy level pair formalism* that we have now developed makes this explicit by considering the entire plasma dynamics in terms of all possible energy level pairs amongst which transitions can occur. It turns out that instabilities occur when the (single particle) down transition frequencies ( $\approx\Omega$ ), for a set of pairs, exceed the up transition frequencies ( $\approx\omega$ ) of a set of pairs. The depolarization shift effects, which reduce the down frequencies to  $\Omega'$ , and increase the up frequencies to  $\omega'$ , bring them into resonance ( $\Omega'=\omega'$ ). *This inter-pair interaction at resonance is what generates plasma instabilities in all cases we have studied.* This work was presented as an invited paper at the 20th International Workshop on Condensed Matter Theory, Pune, India, December 1996, and has been published as Ref. 5.

#### 4. Experimental verification of plasma instabilities.

We have set up a strongly interactive program with the experimental group of Prof. Gornik (Technical University of Vienna), for experimental verification of plasma instabilities as predicted in our work: We held the Third Workshop on Generation and Amplification of Electromagnetic Radiation in MM/SMM Range through Plasma Instabilities at Boston College on August 7-9, 1996. Participants included, besides us, Dr. Mikael Ciftan (ARO), and Prof. Erich Gornik (Vienna). The Fourth Workshop was held at the Technical University of Vienna on November 14-16, 1996, and was hosted by Prof. Gornik. Other participants included, besides us, Dr. Mikael Ciftan (ARO), and from Vienna, Dr. Karl Unterrainer, Dr. Gottfried Strasser, and doctoral candidates Christoph Rauch and Winfried Boxleitner. The Fifth Workshop was held at Boston College, May 29-31, 1997, and besides the Boston College group, the participants included Dr. Mikael Ciftan, Prof. Gornik, Dr. Strasser and Mr. Rauch.

New structures were designed during our visit to Vienna (1996), to achieve a plasma instability based on the general principles described above in Topic 3. These structures were fabricated by molecular beam epitaxy and their I-V curves were measured. We have found a strong support for the possibility of population inversion in these structures studied, by comparing our calculated I-V curves (with and without population inversion) with the experimental curves. Only the curve calculated with the assumption of strong population inversion agrees with the experiment. Some of these results are presented

at the 1998 ICPS'24 Conference in Jerusalem, (Ref. 6) and are submitted for publication to Journal of Applied Physics. (Ref. 7).

A decisive test for plasma instability in these structures is to look for radiation in the predicted frequency range. These experiments, using bow-tie antennas, are planned for the near future.

### 5. Formalisms for inter-level transport and extraction rates.

In the steady state operation, a constant current flows through the entire structure. In the active region the incoming carriers enter through one set of energy levels, and the outgoing carriers are extracted from another set of levels. Ideally, there will be no direct current going across the structure through any single level. The transport inside the active region has to take place through *inter-level transitions*. The inter-level transport occurs amongst these levels through various physical processes such as phonon, photon and plasmon emission and absorption, and carrier-carrier interactions (e.g. Auger type).

We have developed a comprehensive formalism based on the calculation of the self-energy of the carriers in the system under RPA which recognizes that both the plasmon emission and Auger process are part of the same total many-body interactions of all the carriers. It can be shown that the so-called Auger process constitutes only the first diagram in an infinite series which is summable under RPA. Adding the phonon and photon emission and absorption rates, using the standard methods, we can take into account all the interlevel processes in the active region under non-equilibrium steady state conditions. The extraction rates are calculated by the transfer matrix method. The balance equations then determine the partial population  $f_j$  of each level  $E_j$ . This provides the population distribution to be used for the plasma instability calculation in Topic 3.

Part of this work was presented at the 1998 APS March Meeting (Bull. Amer. Phys. Soc. 43, 484, 1998) and has been used to obtain the results in Refs. 6 and 7.

### 6. Other Topics

In addition to these activities, we presented a paper, on "Collective vs. Individual Dot Response of Quantum Dot Ensembles", at the Strongly Coupled Coulomb Systems Conference held at Boston College, August 1997, published as Ref. 8.

### References for Section III

1. H. Xie, "Current Driven Plasma Instability in Lower Dimensional Solid State Systems," Ph.D. thesis, Boston College (1997).
2. P. Bakshi and K. Kempa, "Current Driven Plasma Instabilities in Lower Dimensional Systems," *Superlattices and Microstructures*, 17, 363-372 (1995).
3. H. Xie, P. Bakshi, A. Scorupsky, K. Kempa, "Dispersion and Damping of Plasmons in a Periodically Modulated Quasi-one Dimensional Quantum Wire," to be submitted to *Phys. Rev. B*.
4. K. Kempa, P. Bakshi and E. Gornick, "Plasma Instabilities in a Steady-State Nonequilibrium One-Dimensional Solid-State Plasma of Finite Length," *Phys. Rev. B*, 54, 8231-8234 (1996).
5. P. Bakshi and K. Kempa, "Mathematical Signatures of Plasma Instabilities in Low Dimensional Systems," *Condensed Matter Theories*, Vol. 12, 399-412 (1997). Eds. J. Clark and P. Panat, Nova Science Publishers, New York.
6. K. Kempa, P. Bakshi, C. Du, A. Scorupsky, G. Feng, E. Gornik, G. Strasser, K. Unterrainer and C. Rauch, "Inter-Subband Scattering Rates, Population Inversion and Stimulated Emission of THz Plasmons in Bounded Quantum Systems," paper presented at the 24th International Conference on the Physics of Semiconductors, Jerusalem, August 3-7, 1998.
7. K. Kempa, P. Bakshi, C. Du, G. Feng, A. Scorupsky, G. Strasser, C. Rauch, K. Unterrainer and E. Gornik, "Towards Stimulated Generation of Coherent Plasmons in Nano-structures," submitted to *J. Appl. Phys.*
8. P. Bakshi and K. Kempa, "Collective vs. Individual Dot Response of Quantum Dot Ensembles," *Strongly Coupled Coulomb Systems*, pp 517-521 (1998), ed. G. Kalman et al, Plenum Press.

## IV. Publications and Personnel.

### a) Publications

1. P. Bakshi and K. Kempa, "Current Driven Plasma Instabilities in Lower Dimensional Systems," *Superlattices and Microstructures*, **17**, 363-372 (1995).
2. K. Kempa, P. Bakshi and E. Gornick, "Plasma Instabilities in a Steady-State Nonequilibrium One-Dimensional Solid-State Plasma of Finite Length," *Phys. Rev. B*, **54**, 8231-8234 (1996).
3. P. Bakshi and K. Kempa, "Mathematical Signatures of Plasma Instabilities in Low Dimensional Systems," *Condensed Matter Theories*, Vol. 12, 399-412 (1997). Eds. J. Clark and P. Panat, Nova Science Publishers, New York.
4. H. Xie, "Current Driven Plasma Instability in Lower Dimensional Solid State Systems," Ph.D. thesis, Boston College (1997).
5. K. Kempa, P. Bakshi, C. Du, A. Scorupsky, G. Feng, E. Gornik, G. Strasser, K. Unterrainer and C. Rauch, "Inter-Subband Scattering Rates, Population Inversion and Stimulated Emission of THz Plasmons in Bounded Quantum Systems," paper presented at the 24th International Conference on the Physics of Semiconductors, Jerusalem, August 3-7, 1998.
6. P. Bakshi and K. Kempa, "Collective vs. Individual Dot Response of Quantum Dot Ensembles," *Strongly Coupled Coulomb Systems*, pp 517-521 (1998), ed. G. Kalman et al, Plenum Press.
7. K. Kempa, P. Bakshi, C. Du, G. Feng, A. Scorupsky, G. Strasser, C. Rauch, K. Unterrainer and E. Gornik, "Towards Stimulated Generation of Coherent Plasmons in Nano-structures," submitted to *J. Appl. Phys.*
8. H. Xie, P. Bakshi, A. Scorupsky, K. Kempa, "Dispersion and Damping of Plasmons in a Periodically Modulated Quasi-one Dimensional Quantum Wire," to be submitted to *Phys. Rev. B*.

### b) Personnel

1. Prof. P. Bakshi (Faculty), Principal Investigator
2. Prof. K. Kempa (Faculty), Principal Investigator
3. H. Xie (Graduate Student), Research Assistant
4. A. Scorupsky (Graduate Student), Research Assistant
5. V. Valtchinov (Graduate Student), Research Assistant
6. Dr. C. Du, Research Scientist

### c) Degree earned.

H. Xie: Ph.D., Boston College (1997)

### d) Reportable inventions.

None